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Two New and Remarkable Sightlines into the GC's Molecular Gas

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ABSTRACT

Until now the known sources in the Galactic center with sufficiently smooth spectra and of sufficient brightness to be suitable for high resolution infrared absorption spectroscopy of interstellar gas occupied a narrow range of longitudes, from the central cluster of hot stars to approximately 30 pc east of the center. In order to more fully characterize the gas within the r $\sim$ 180 pc central molecular zone it is necessary to find additional such sources that cover a much wider longitudinal range of sightlines. We are in the process of identifying luminous dust-embedded objects suitable for spectroscopy within 1.2° in longitude and 0.1° in latitude of Sgr A* using the *Spitzer* GLIMPSE and the Two Micron All Sky Survey catalogues. Here we present spectra of H_3^+ and CO towards two such objects, one located 140 pc west of Sgr A*, and the other located on a line of sight to the Sgr B molecular cloud complex 85 pc to the east of Sgr A*. The sightline to the west passes through two dense clouds of unusually high negative velocities and also appears to sample a portion of the expanding molecular ring. The spectra toward Sgr B reveal at least ten absorption components covering over 200 km s^{-1} and by far the largest equivalent width ever observed in an interstellar H_3^+ line; they appear to provide the first near-infrared view into that hotbed of star formation.

Subject headings: Galaxy: center — ISM: clouds — ISM: lines and bands — ISM: molecules

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1. Introduction

The Galactic center (GC) is a fascinating environment containing a multitude of extraordinary phenomena and extraordinary objects, not the least of which are three dense clusters of young and hot stars and a multi-million solar mass black hole. Until recently it was thought that the interstellar gas within the central few hundred parsecs of the Galaxy, usually referred to as the central molecular zone (hereafter CMZ) consisted of three major components (Morris & Serabyn 1996; Lazio & Cordes 1998): ultra high temperature X-ray-emitting plasma; ionized gas at T$\sim 10^{4-6}$ K responsible for the well-studied fine structure and radio recombination line emission; and cool and dense molecular clouds, which have also been observed in considerable detail at radio wavelengths. However, recent infrared spectroscopy of H_3^+ and CO, and in particular of the key $R(3,3)^l$ absorption line from a metastable state of H_3^+ (Goto et al. 2002; Oka et al. 2005), has clearly revealed the presence of another component, which in terms of density (50–200 cm^{-3}) has the characteristics of Galactic diffuse cloud material, but which is considerably warmer (200–300 K). At present, this warm dilute environment is unique to the GC; it has not been found in any other Galactic diffuse clouds surveyed in H_3^+ (Geballe & Oka, unpublished data). It appears to include gas associated with the r $\sim$ 180 pc expanding molecular ring (hereafter EMR; Kaifu et al. 1972; Scoville 1972), which has also been characterized as an expanding molecular shell (Sofue 1995), located at the outer edge of the CMZ.

Because of the unique properties of H_3^+ (e.g., Geballe 2006), observations of H_3^+, combined with those of CO, are key to characterizing the physical conditions in the CMZ and the extent of the warm and diffuse component there. However, spectroscopy of H_3^+ is difficult because its lines are weak owing to its low abundance. Until recently there has been available as probes of the line of sight to the GC only a small number of hot stars in the Central cluster and in or near the Quintuplet cluster 30 pc east, which are both sufficiently bright for high resolution spectroscopy and have smooth infrared spectra so that the H_3^+ line profiles are uncontaminated by photospheric absorption lines in the background source.

Spectra of these already-known sources (Oka et al. 2005; Goto et al. 2008) have shown that the warm and diffuse component is present on every sightline and also have shown that the H_3^+ column lengths are substantial fractions of the radius of the CMZ. They thus suggest that the diffuse and warm environment in which the H_3^+ is located takes up a large fraction of the volume in the central few hundred parsecs. If correct, this would strongly contradict the previous conceptual picture of GC gas, e.g., as illustrated in Lazio & Cordes (1998), in which a warm and diffuse component has not been included at all.

To better evaluate the extent and physical nature of this newly discovered environment, sightlines providing a wider coverage of the CMZ are needed. It is therefore essential to find

additional bright sources with featureless or nearly featureless spectra – either hot stars with few emission or absorption lines, or stars encased in dense shells of warm dust – in a more extended region of the GC.

2. Finding New Sightlines through the CMZ

The CMZ is filled with bright infrared sources, but everywhere except at locations of the three clusters of luminous hot stars (the Central, Arches, and Quintuplet clusters) the overwhelming majority of them are red giants, whose complex photospheric absorption spectra make them unsuitable as probes of the interstellar medium. Until very recently, no smooth-spectrum objects in the line of sight to the CMZ but far from those clusters were known. We are using the Two Micron All Sky Survey (2MASS) Point Source catalogue (Skrutskie, et al. 2006) and the *Spitzer Space Telescope* GLIMPSE catalogue (Ramírez et al. 2008) to identify bright objects in the direction of the CMZ that are likely to have opaque dust shells. A simplified description of the technique is that the shorter wavelength IR colors are mainly used to weed out foreground (low extinction) sources and "normal" red giants, and the longer wavelength IR colors are mainly used to identify emission from warm dust. However, the situation is far from straightforward, because the effects on 1–8 μm photometry of high extinction and low temperature cannot be easily separated. Our success rate, although much higher than a random sampling, is currently only $\sim$15%.

Thus a check of each candidate is necessary before proceeding to the time-consuming high-resolution spectroscopy. This second step is performed by obtaining quick medium-resolution K-band spectra, in particular covering the first overtone CO bands at 2.3–2.5 μm, to determine if the candidates do indeed have smooth spectra or are cool red giants suffering high extinction.

Our requirement for high resolution spectroscopy of the key lines of H_3^+, which mostly lie in the 3.5–3.7 μm region, is that the sources have Infrared Array Camera (IRAC) band 1 (3.6 μm) magnitudes brighter than 8. Roughly 2,000 GLIMPSE sources with $-1.2^\circ < l < +1.2^\circ$ and $-0.1^\circ < b < +0.1^\circ$ (here l and b are offsets in Galactic longitude and latitude from Sgr A*, assumed to be at a distance of 8.0 kpc) satisfy that criterion. Most of them have 2MASS counterparts. Based on 2MASS $J-K$, 2MASS/Spitzer $K-$IRAC(1) and Spitzer IRAC(1)$-$IRAC(4) (8.0 μm) colors, we have compiled a list of $\sim$250 candidate dusty sources that to our knowledge had not previously been observed spectroscopically. K-band spectra of approximately 75 of them now have been obtained. Of those, ten, whose locations are shown in Figure 1, have been found to be suitable for high resolution spectroscopy of interstellar gas lines. We have no additional information concerning the natures of these ten

sources. They are likely to contain either young stellar objects or luminous evolved stars.

At the stage that the K-band spectroscopy has revealed suitable sources, the locations of those sources along the line of sight are unknown. Although we attempt to select for high interstellar extinction, it is quite possible that some of the sources are situated in front of the GC. High resolution spectroscopy of CO first overtone lines originating in low J levels of the ground vibrational state can help to locate the sources on the line of sight. Previous observations by Oka et al. (2005) have demonstrated that the spectra of objects in the GC show narrow absorption components of H_3^+ and CO arising in foreground spiral arms. The presence or absence of absorption components at the characteristic velocities of these foreground arms can provide useful constraints. However, the clouds along the intervening spiral arms may not be continuous, but instead clumpy on small scales. Thus the lack of an absorption at a velocity characteristic of a spiral arm does not necessarily prove that the object is located in front of that arm.

Despite the low efficiency and the possibilities of confusion about location on the line of sight, the technique already shows great promise of providing a more extensive and more unifom sampling of the molecular gas in the CMZ than previously available. In particular, the sightlines toward two of newly found objects, 2MASS J174332173−2951430 and 2MASS J17470898−2829561 (hereafter 2M1743 and 2M1747, respectively), contain remarkable collections of interstellar clouds absorbing in lines of CO and H_3^+. In the following sections we describe the exploratory spectra we have obtained of them.

3. Medium Resolution Spectra

Medium-resolution 1.4–2.5 μm spectra of 2M1743 (K = 6.5) and 2M1747 (K = 10.4) were obtained at the United Kingdom Infrared Telescope (UKIRT) on Mauna Kea on 2008 July 28 and August 15, respectively, using the facility imager/spectrograph UIST, whose 0.2″ wide slit provided a resolving power of 1000. On both nights HR 6409 (F6 IV) was observed at roughly the same air mass as the 2MASS objects for the purposes of flux calibration and removal of telluric lines. Total integration times on the 2MASS objects were 80 and 360 seconds, respectively. Observations were made in stare/nod-along-slit mode. Data reduction was standard for near-infrared spectroscopy of point sources. Wavelength calibration was obtained from telluric absorption lines observed in HR 6409 and is accurate to better than 0.0005 μm. The 2.166 μm Br γ absorption line in HR 6409 was removed by interpolation prior to ratioing.

The 2.0–2.4 μm portions of the spectra of the two objects are shown in Fig. 2. 2M1743

has a smooth and steeply rising spectrum, consistent with that of a dust-embedded star. The spectrum of 2M1747, which rises even more steeply, is also indicative of warm dust. However, while the spectrum of 2M1743 appears featureless at this resolution, that of 2M1747 shows several significant absorptions. These include the 2–0 and 3–1 band heads of CO, perhaps originating in the veiled photosphere of a cool and luminous star or in a dense and high-temperature circumstellar shell or disk of a young stellar object. In addition, significant absorption is seen near the wavelength of the 2–0 CO band center (2.347 μm), suggesting the presence of an unusually large column density of lower temperature (interstellar) CO. Finally, a broad absorption band, centered at approximately 2.265 μm, is present. It has a full width at zero intensity of $\sim$ 0.02 μm. We are unable to identify this feature. Its wavelength range encompasses that of the triplet of neutral calcium lines seen in late-type stars (Kleinmann & Hall 1986); however, the feature is too broad and too strong relative to CO for that identification to be viable. It is possible that the absorption is produced in frozen grain mantles within molecular clouds along the line of sight. An absorption at 2.27 μm with a similar profile, possibly due to solid methanol, has been observed in some solar system objects (Cruikshank et al. 1998).

4. High Resolution Spectra of H_3^+ and CO

High resolution spectra of both objects at the $R(1{,}1)^l$ transition of H_3^+ near 3.715 μm and covering a small portion of the 2–0 band of CO near 2.342 μm were obtained at the Gemini South telescope on Cerro Pachon in Chile on 2009 July 6. The observations used the echelle spectrograph, Phoenix, whose 0.34$''$ wide slit provides a resolving power of 50,000. In one setting the spectral coverage corresponds to $\Delta\lambda/\lambda$ = 0.0045 on the instrument's detector array. For the CO spectra the echelle was centered at 2.342 μm, thereby covering the five lowest lying R branch transitions of the 2–0 band, i.e., $R(0)$–$R(4)$. The separation of adjacent 2–0 rovibrational CO lines corresponds to a velocity range of 260 km s−1; thus if the absorption profile is broad the baseline for defining the continuum level between CO lines is restricted. The other setting was centered on the wavelength of the H_3^+ line, whose lower level is the ground state. Data reduction was similar to that described earlier, with HR 6070 (A0V) and HR 7254 (A2V) serving as standards for both wavelength intervals. Wavelength calibrations used telluric absorption lines, and the resultant velocity scales in Figures 3 and 4 are accurate to 2 km s^{-1}.

4.1. 2MASS J17432173−2951430

Profiles of the H_3^+ line and the CO $R(0)$–$R(3)$ lines observed toward 2M1743 are shown in Figure 3. Absorption components of CO are present at LSR velocities of −60, −172, and −200 km s^{-1}. The −172 km s^{-1} absorption profile is slightly asymmetric, indicating the presence of a second and weaker absorption red-shifted by a few km s^{-1}. The H_3^+ $R(1,1)^l$ spectrum also contains prominent absorption components, including the same three seen in CO, and a red-shifted shoulder on the −172 km s^{-1} absorption that is relatively stronger than in CO. A fourth prominent absorption in the H_3^+ spectrum, which is not present in CO, is an apparent velocity doublet at 0 and +8 km s^{-1}. Finally, broad but weaker H_3^+ absorptions, which also have no counterparts in CO, are centered near −27 and −75 km s^{-1}.

The CO absorptions observed at −60, −172, and −200 km s^{-1} are likely to be formed in dense clouds. Only the first four rotational levels are significantly populated. The overall CO excitation temperature is roughly 10 K, but it is quite possible that the kinetic temperature is higher and that the level populations are sub-thermal. A more thorough analysis will be provided in a subsequent paper. The component at -60 km s^{-1} possibly arises in the 3 kpc arm. On sightlines much closer to the center the absorption ascribed to that spiral arm occurs near −52 km s^{-1} (Oka et al. 2005). The other two CO components, at much higher velocity, do not correspond to foreground spiral arms. Because of their high velocities it is likely that these features arise close to the GC. CO J=1–0 spectra obtained by Oka et al. (1998) approximately along this sightline ($l_{II} = 358.954°$, $b_{II} = −0.066°$) have their strongest emission components at those two high negative velocities.

Because no infrared CO absorption is present at the velocities of the H_3^+ absorptions near 0, +8, and −75 km s^{-1}, the clouds producing them must be diffuse. Only weak CO J=1–0 line emission is present at those velocities. 2M1743 is located within a few parsecs of the galactic plane and is approximately 140 pc west of the center (see Figure 1). If it is located somewhat behind the center, its sightline would cross the EMR where its gas is moving nearly in the plane of the sky (with very little Doppler shift). It is thus logical to associate the low velocity doublet with the EMR and to place 2M1743 somewhat behind the EMR. Previous observations have demonstrated that the EMR contains diffuse gas (Oka et al. 2005; Goto et al. 2008). If the identification is correct, it is evidence that the diffuse nature of the EMR's gas is widespread, and is not limited to the sightlines close to the longitudes of the Central and Quintuplet clusters.

We have no specific identification for the H_3^+ features at −27 km s^{-1} and −75 km s^{-1}. However, previously observed GC slightlines (Oka et al. 2005; Goto et al. 2008) showed a trough of absorption by diffuse gas from 0 to −100 km s^{-1}, indicating that a significant fraction of the volume of the CMZ contains diffuse gas. If so, then the presence of additional

H_3^+ absorption components in that velocity range would not be surprising.

4.2. 2MASS J17470898−2829561

Velocity profiles of the H_3^+ line and the CO $R(0)$–$R(3)$ lines toward 2M1747 are displayed in Figure 4. Both molecules absorb continuously over wide velocity ranges. Absorption by CO extends without interuption from −100 to +100 km s^{-1}, and the absorption by H_3^+ extends even further without a break, from −130 to +100 km s^{-1}. About a dozen discrete velocity components can be seen in both the H_3^+ and CO line profiles. Several, but not all of the components of the two molecules coincide, and thus the sightline appears to contain a combination of diffuse and dense clouds, but at present it is not possible to untangle the two contributions. The only clear indication of gas with a low excitation temperature similar to that seen in the CO toward 2M1743 is at −43 km s^{-1}, where the strongest absorption occurs in the $J = 0$, 1, and 2 levels and where the CO absorption depth noticeably decreases with increasing lower state energy. This absorption component may be a continuation of absorption by molecular gas in the 3 kpc arm, as discussed previously for 2M1743.

At $l_{II} = 0.548°$, $b_{II} = -0.060°$, 2M1747 is located approximately 85 pc east of the Galactic center on the line of sight to the Sgr B giant molecular cloud complex, and is almost directly between Sgr B1 and Sgr B2 (Figure 1). The CO J=1–0 spectra of Oka et al. (1998) at this location shows a strong and complex emission profile at positive velocities, not very different from those seen in the infrared CO and H_3^+ lines, but very little emission at negative velocities where both the infrared CO and H_3^+ absorptions also are strong.

Given the unprecedented large widths of the H_3^+ $R(1,1)^l$ and interstellar CO lines (that of the H_3^+ line is roughly twice that previously reported for any other GC sightline), it seems beyond doubt that 2M1747 lies within Sgr B. To our knowledge the absorption spectra in Figure 4 are the first near-infrared views into that complex and turbulent star-forming region.

5. Conclusion

The spectra presented here represent the beginning of a new phase of exploration of the CMZ using absorption spectroscopy of H_3^+ and CO along new sightlines, which has already yielded striking results. More detailed understanding of the gas on these two new sightlines, as well as on others that have been or are likely to be found, will require spectroscopy of additional transitions of H_3^+, in particular of the $R(2,2)^l$ and $R(3,3)^l$ lines, arising from higher energy levels than the $R(1,1)^l$ line, and detailed comparison with infrared and millimeter

spectra of CO and perhaps other molecular species.

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REFERENCES

Cruikshank, D. P., et al. 1998, Icarus, 135, 389

Downes, D. & Maxwell, A. 1966, ApJ, 146, 653

Geballe, T. R. 2006, Phil Trans. Roy. Soc. A, 364, 3035

Goto, M., McCall, B. J., Geballe, T. R., Usuda, T., Kobayashi, N., Terada, H., & Oka, T. 2002, PASJ, 54, 951

Goto, M., et al. 2008, ApJ, 668, 306

Kaifu, N., Kato, T., & Iguchi, I. 1972, Nature Phys. Sci., 238, 105

Kleinmann, S. G. & Hall, D. N. B. 1986, ApJS, 62, 501

Lazio, T. J. W., & Cordes, J. M. 1998, ApJ, 505, 715

Morris, M., & Serabyn, E. 1996, ARA&A, 34, 645

Oka, T., Geballe, T. R., Goto, M., Usuda, T., & McCall, B. J. 2005, ApJ, 632, 882

Oka, T., Hasegawa, T., Sato, F., Tsuboi, M., & Miyazaki, A. 1998, ApJS, 118, 455

Ramírez, S. V., Arendt, R. G., Sellgren, K. Stolovy, S. R., Cotera, A., Smith, H. A., & Yusef-Zadeh, F. 2008, ApJS, 175, 147

Scoville, N. Z. 1972, ApJ, 175, L127

Skrutskie, M. F., et al. 2006, AJ, 131, 1163.

Sofue, Y. 1995, PASJ, 47, 551

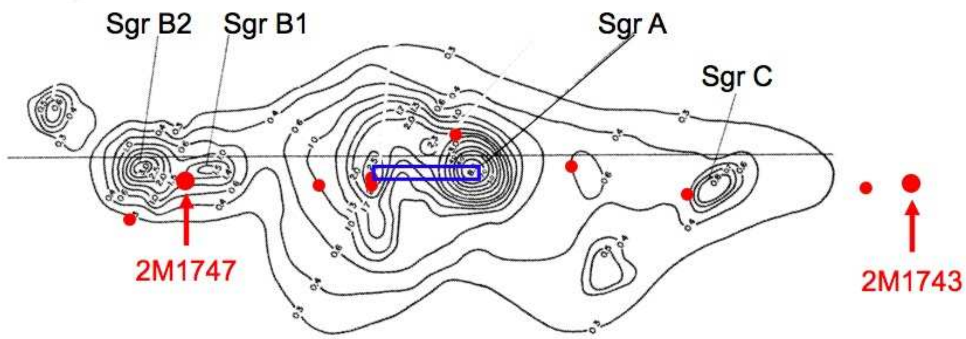

Fig. 1.— A portion of a radio contour map of the GC at 8.0 GHz (Downes & Maxwell 1966), with principal radio sources labelled. Locations of 2MASS J17432173−2951430 and 2MASS J17470898−2951430 are indicated by large red dots and arrows; locations of other newly discovered smooth spectrum 2MASS sources are indicated by small dots. Locations of sources previously observed in H_3^+ lines fall within the narrow blue rectangle. The horizontal line denotes the Galactic plane ($b_{II} = 0°$).

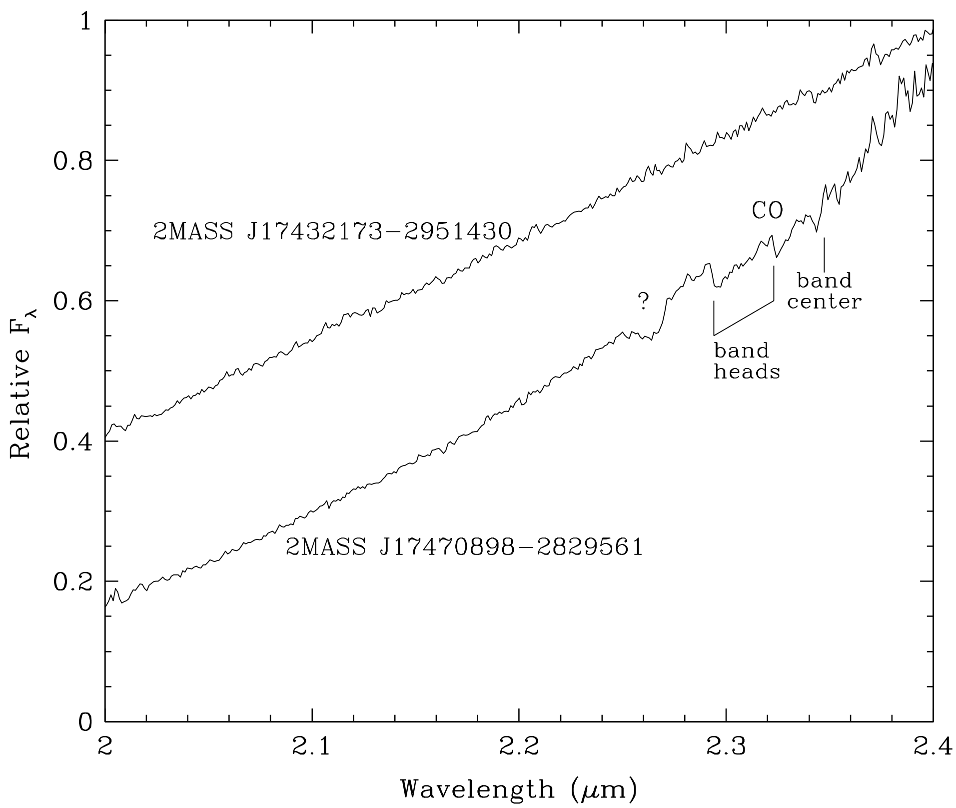

Fig. 2.— Medium resolution 2.0–2.4 μm spectra of two sources identified as likely dust-embedded stars located close to the GC. Locations of spectral features are indicated and identified if known.

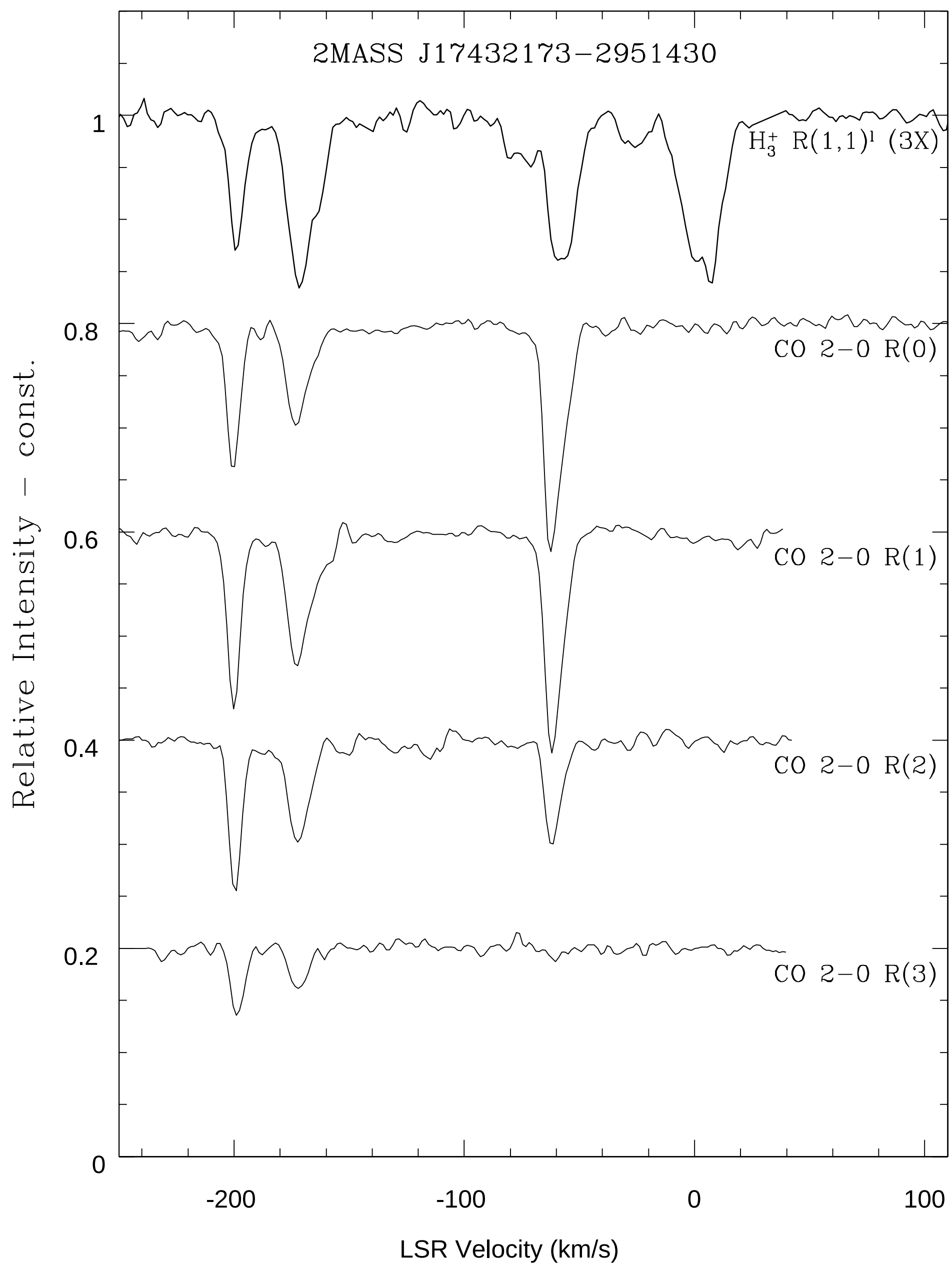

Fig. 3.— Spectra of the $R(1,1)^l$ line of H_3^+ and the four lowest lying transitions of the 2−0 R branch of CO in 2MASS J17432173−2951430. Spectra are offset vertically. CO spectra are to the same scale; an opaque CO line would have depth unity. The H_3^+ spectrum is magnified by a factor of 3. Noise can be judged by point-to-point fluctuations in flat regions of the spectra.

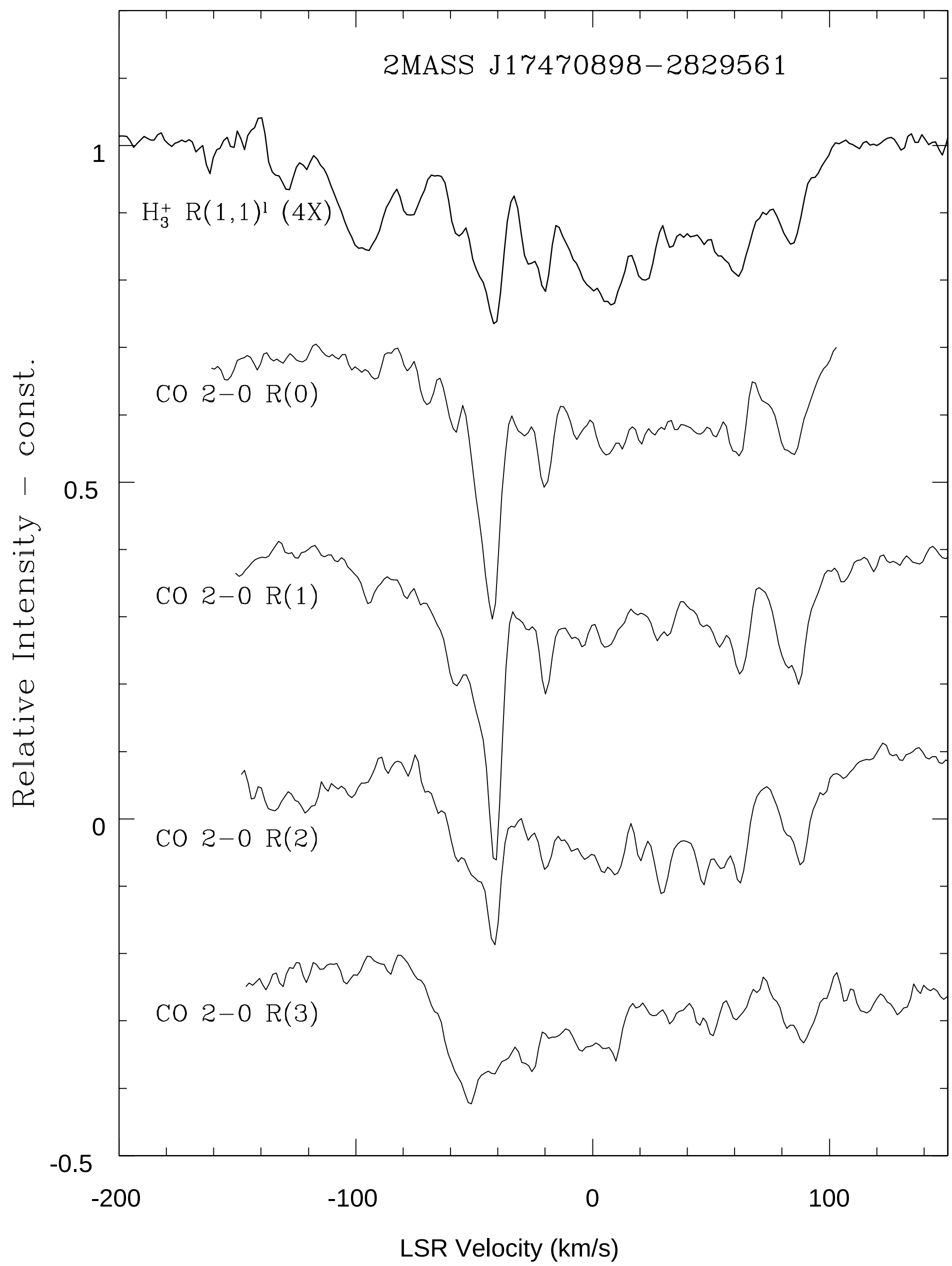

Fig. 4.— Spectra of the $R(1,1)^l$ line of H_3^+ and the four lowest lying transitions of the 2−0 R branch of CO in 2MASS J17470898−2951430. CO spectra are to the same scale; an opaque CO line would have depth unity. The H_3^+ spectrum is magnified by a factor of 4.